Effects of the Initial Boundary-Layer State on Turbulent Jet Mixing

William G. Hill Jr.,* Richard C. Jenkins,†
and
Barry L. Gilbert‡
Grumman Aerospace Corp. Bethpage, N. Y.

Theme

A MAJOR problem in many jet mixing flows is scaling, since research and development tests are usually done at much lower Reynolds numbers than the full scale application. It often occurs that if no special tripping is done, the initial boundary layer in the jet of a subscale test is laminar, while the full scale hardware will have a turbulent boundary layer. One of the primary goals of our investigation of initial boundary - layer effects was to evaluate the importance of this difference on the accuracy of full scale predictions deduced from model tests. Secondary objectives included a study of the reasons for the differences in core lengths obtained by different investigators and possible isolation of particular boundary-layer characteristics that enhance turbulent mixing rates.

Both axisymmetric and two-dimensional free jet flowfields exhibit a power law dependence for the decay of centerline velocity with distance from nozzle exit at points that are well downstream of the initial mixing region. However, variations in shear layer properties close to the jet exit can cause the centerline velocity profile to shift upstream or downstream under different operating conditions. Measurements made by different investigators in flowfields produced by similar nozzles frequently show significant variations in core length; the far field centerline velocity decay, however, follows a predictable variation with axial distance.[1] Much of this earlier research on turbulent mixing in free jets has addressed cases where the effects of initial conditions were intentionally minimized. The few cases in which data regarding initial conditions are available indicate that the effects of nozzle boundary layers on mixing rates are often significant. While there are many aspects of turbulent mixing that warrant further investigation, it was the consensus of both the attendees and the review committee at the Langley Working Conference on Free Turbulent Shear Flows[2] that the effect of initial conditions is a primary area requiring study.

In this paper we describe some effects of nozzle wall boundary-layer conditions on incompressible air jets discharging into quiescent surroundings. This investigation included the influence of the boundary-layer state on the turbulent mixing layer surrounding axisymmetric and two-dimensional free jets and on time averaged measurements obtained in these flows.

Contents

This paper summarizes the results of Refs. 3 and 4 for the effect of the initial boundary layer on turbulent jet mixing rates. Turbulent initial boundary layers were found to produce consistent jet mixing rates over a range of velocity, boundary-layer thickness, and geometry. Laminar initial boundry layers resulted in jet mixing rates that varied with both the primary variables and such secondary factors as supply fan characteristics. The jets resulting from laminar initial boundary layers generally were found to have faster mixing rates, a different turbulence intensity signature, and a much more prominent large scale structure than the jets having a turbulent initial boundary layer. It is clear that scale model tests involving jet plume simulation require turbulent initial boundary layers to avoid the possibility of producing erroneous turbulent mixing results such as entrainment or impingement effects.

The work reported in Ref. 3 included data obtained from several experimental facilities. Laminar boundary-layer thickness was varied by altering the length of the constant area section of the nozzle, and turbulent boundary layers were produced with trips. Boundary-layer and flowfield measurements were obtained with a hot film anemometer using cylindrical probes 0.0025 cm in diameter. The probes were traversed through the boundary layer 0.06 cm upstream of the nozzle exits using a vernier drive. The boundary-layer state was determined from the turbulence level and velocity profile characteristics of the anemometer output. Axisymmetric nozzles were 2.54, 5.08, or 10.16 cm in diameter. The two-dimensional nozzles had width $W=26.7$ cm with height $H=2.54$ or 1.27 cm. Nozzle exit velocities (U_0) were between 6 and 230 m/sec, providing a Reynolds number range (based on nozzle exit dimensions) from 10^5 to 1.5×10^7.

All of the data presented here were obtained in the flow from a two-dimensional nozzle ($H=2.54$ cm by $W=26.7$ cm) having a 15.2 cm length of constant cross section. A 0.025 cm thick tape trip was used near the nozzle entrance to obtain turbulent boundary-layer conditions. The air supply facility consisted of a settling chamber with 0.61 meter square cross section that was powered by a 0.75 kW centrifugal fan.

The jet velocity profiles were obtained using a linearized hot film anemometer with the analog signal continuously displayed versus probe location on an *x-y* recorder. The absolute accuracy of this data was within 5%. However, the repeatability of the measurements (important for comparing consecutive profiles taken with altered initial conditions) was established to be within 1%.

When the initial boundary layer was laminar, the centerline velocity decay and turbulence intensity downstream of the nozzle lip varied with the jet velocity, as shown in Figs. 1 and 2.

In contrast, when the boundary layer was turbulent the results for both the centerline velocity decay and the variation in rms turbulence level downstream of the nozzle lip were independent of velocity as shown in Figs. 3 and 4.

The centerline velocity decay is seen to be generally more rapid with a laminar boundary layer than with a turbulent boundary layer. The turbulence level downstream of the lip is also seen to be much higher close to the exit when the boundary layer is laminar than it is when the boundary layer is turbulent. These same trends were again observed for axisymmetric nozzles and with different values of nozzle diameter, height, boundary-layer thickness, and facility characteristics.

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Index categories: Jets, Wakes, and Viscid-Inviscid Flow Interactions; Viscous Nonboundary-Layer Flows.

*Research Scientist, Research Dept.

†Research Engineer, Research Dept. Member AIAA.

‡Research Scientist, Research Dept. Member AIAA.

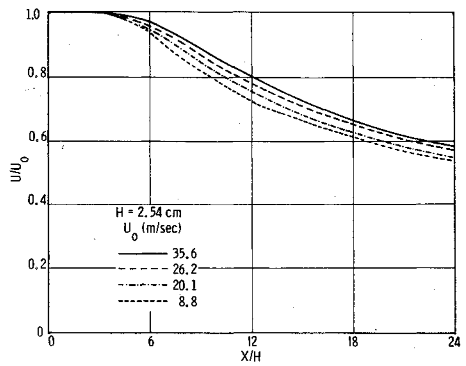

Fig. 1 Centerline velocity decay of a jet from a two-dimensional nozzle with a laminar boundary layer.

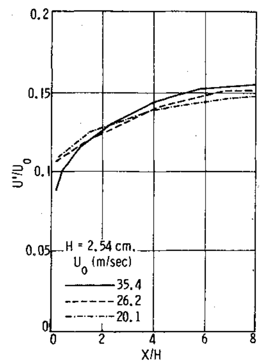

Fig. 4 Turbulence intensity profiles downstream of the lip of a two-dimensional nozzle with a turbulent boundary layer.

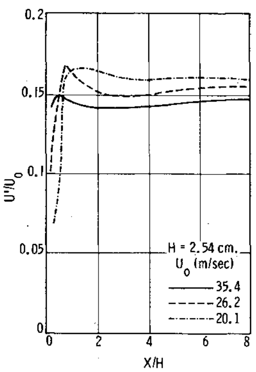

Fig. 2 Turbulence intensity profiles downstream of the lip of a two-dimensional nozzle with a laminar boundary layer.

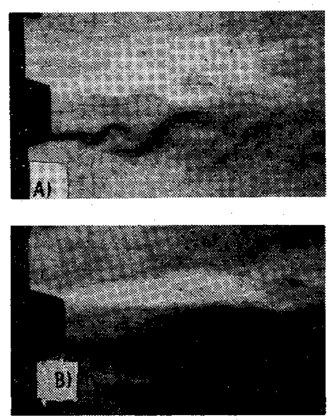

Fig. 5 Effect of boundary-layer state on observable large scale structure. Two dimensional jet- $H=2.54$ cm, $U_0=20.1$ m/sec, spark Schlieren photographs. a) Laminar initial boundary layer. b) Turbulent initial boundary layer.

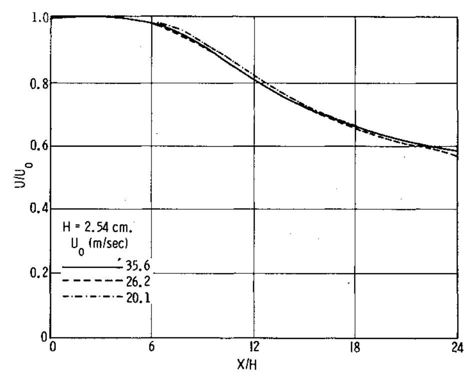

Fig. 3 Centerline velocity decay of a jet from a two-dimensional nozzle with a turbulent boundary layer.

The centerline velocity decay characteristics with a laminar initial boundary layer were found to be sensitive to changes in the apparatus, such as supply fan rpm and settling chamber dimensions. Under all cases tested, the velocity decay did show some variation with jet velocity. The curves of turbulence intensity versus distance downstream of the nozzle lip also showed some variation with test conditions. Under all conditions, however, the turbulence intensity curves showed a much more rapid initial rise with a laminar boundary layer than they did with a turbulent boundary layer. The results of Batt,[5] where an attempt at tripping the boundary layer was unsuccessful, are also in agreement with the characteristics we noted with laminar boundary layers.

We also found that when the jet velocity was decreased beyond a certain point the trip was no longer effective. When this point was reached the jet mixing behavior became similar to that found with an untripped laminar boundary layer.

A series of spark-Schlieren flow visualization experiments was conducted to gain a better understanding of the reasons for the observed differences in mixing rates with laminar and turbulent boundary layers.[4] The results, illustrated in Fig. 5 for a two dimensional nozzle, showed clearly the presence of a coherent, large scale structure in the shear layers when the initial boundary layer was laminar. When the initial boundary layer was turbulent, this structure could not be discerned. These same results were also found for axisymmetric jets and over a range of jet velocities. The initial boundary-layer state therefore seems to play a role in the presense, or at least the strength, of the coherent, large scale structure observed in turbulent mixing. The observed differences in large scale structure for flows with laminar or with turbulent initial boundary layers are consistent with the measured differences in mixing rates and turbulence intensity downstream of the nozzle exit.

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